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Magnetic Designs and Field Quality of Nb_3Sn Accelerator Magnets

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[1]*Abstract*-- **This paper presents a new approach to accelerator magnet design, based on simple and robust single-layer coils with minimum number of turns arranged horizontally or vertically in a common iron yoke. Cos-theta and block type coil geometries as well as cold and warm iron yoke designs were studied. Coils and yokes were optimized for the maximum field, minimum field harmonics, and minimum sizes.**

***Index Terms*—Accelerator dipole magnet, field quality, superconductor**

I. Introduction

FERMILAB is involved in the development of Nb_3Sn accelerator magnets with the nominal field of 10-12 T for a future Very Large Hadron Collider (VLHC). The latest version of VLHC, recently studied at Fermilab, is based on 175 TeV cms beam energy and 233 km circumference [1]. The large machine circumference implies a large number of magnets, which makes it vitally important to simplify their design and develop manufacturing technology, aimed at high reproducibility of their parameters and cost reduction.

The coil, serving as flux-driving and field-forming element is the most critical part of the conductor-dominated accelerator magnet. It usually consists of several tenths of turns subdivided onto several layers and blocks in order to reduce the magnet operating current and provide enough free parameters for the field quality tuning. However, the large number of layers, turns and blocks complicates the magnet fabrication technology, increases manufacturing time and cost, reduces accuracy of the turn/block position due to accumulation of many small errors, restricts the magnet length due to quench protection problems, etc. Experience with the RHIC magnets [2] has demonstrated significant technical and economical advantages of simple single-layer coils. This approach have been used in the design of Nb_3Sn single-layer common coil dipole, developed for VLHC [3].

In this paper, the single-layer coil concept combined with the minimum number of blocks and turns is used in several 2-in-1 dipole designs developed for VLHC. This combination promises a reduction of the magnet cost, manufacturing and testing time and installation expenses.

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II. Magnet Designs

The primary design goal of this work was reaching an accelerator-quality dipole field of 12 T in a 40-50 mm magnet bore using single-layer coils with the minimum number of turns. The second goal was minimizing the total magnet size and weight. In order to achieve this goal, the 2-in-1 approach was used. Both 2-in-1 configurations with vertical and horizontal bore arrangement were considered and studied. Final reduction of the total magnet cross-section and weight was achieved by minimizing the bore separation distance for each configuration and optimizing the iron yoke geometry.

The coils were optimized using the ROXIE code [4]. The cross-sections of the iron yoke were optimized using the OPERA2D code.

A. Coil cross-section

Single-layer coils of two types (cos-theta and block) were considered during simulations and referred to as Design I and Design II. Fig. 1 presents the coil cross-sections with the field quality diagrams. The coil geometry was optimized for the round iron yoke with the minimum coil to yoke distance of 8 mm and the iron permeability μ_r=1000 [5].

Design I coil is based on the shell type (cos-theta) geometry. In order to approximate the cos-theta azimuthal distribution of current, six turns grouped into three blocks per quadrant, as shown in Fig. 1 (left), is required. The target coil bore diameter of 45 mm and the target quench field of 12 T define the cable dimensions of 3.942x26.717 mm^2 at 0.25 mm thick cable insulation. The manufacturing considerations explained in the next section require the rectangular cross-section of the cable. The block positions and tilt angles were optimized for the best field quality in the coil bore. A slight ellipticity introduced in the bore geometry helpes reaching a better field quality with respect to the round bore case.

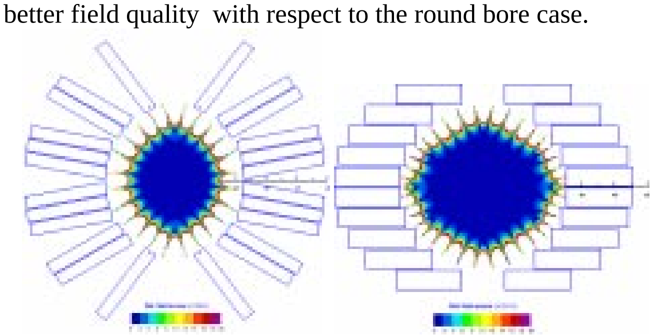

Fig. 1. Coil geometry with the field quality ($\Delta B/B$) diagram (Design I – left, Design II - right). Increment between adjacent zones is $0.2\cdot10^{-4}$.

Design II coil is based on the block type geometry with horizontally positioned and stacked turns (see Fig. 1, right). Five turns per quadrant are sufficient for approximation of the intersecting ellipses, generating a uniform field in the aperture. The number of turns, the coil bore diameter and the target field determine the cable dimensions of 5.935x20.233 mm^2 for 0.25 mm thick cable insulation. The horizontal position of each turn was optimized to achieve the best field quality in the bore.

The calculated coil parameters are summarized in Table I.

TABLE I
COIL PARAMETERS

Parameter	Design I	Design II
Coil bore in midplane, mm	45.0	50.0
Available round bore, mm	45.0	45.0
Number of turns	12	10
Coil area, cm^2	22.6	22.8

B. Coil support structures

Fig. 2 shows possible mechanical support structures for Design I and Design II coils.

The support structure of Design I consists of stainless steel collar laminations with rectangular slots for each block, ensuring the nominal cable positions. The specific feature of this design is that the wedges, separating the coil blocks, are part of the collar structure. It prevents an accumulation and transfer of the azimuthal component of the Lorentz force to the midplane blocks.

The support structure of Design II consists of outer stainless steel or aluminum collar laminations and an inner insert. The collars and the insert have rectangular steps for placing each turn in its nominal position. The inner insert also serves for the partial reaction to the vertical component of the Lorentz force in the pole turns.

The large horizontal component of the Lorentz forces will be reacted in both designs by the collar, the yoke and the cold mass skin.

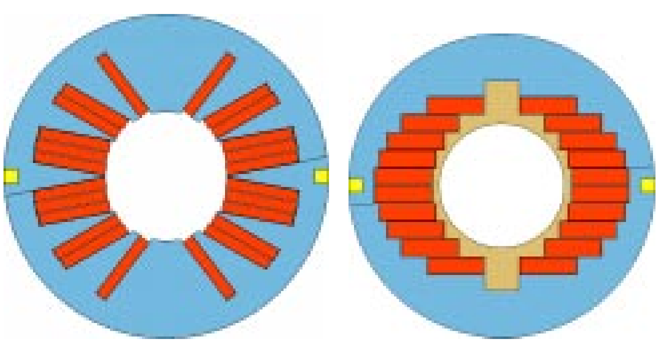

Fig. 2. Mechanical structures of the collared coils.

C. Fabrication approach

Due to the small bending radii of turns in end regions, Design I coil is better suited for the wind-&-react fabrication technique. Each half-coil is wound directly into the coil support structure described above. After that, the two collared half-coils are assembled around the mandrel and collars are locked together by keys. All gaps between cables and the collar, necessary for easy cable installation into the slots, will be removed and some small azimuthal prestress will be created due to the Nb_3Sn expansion during reaction [6]. Afterwards, the collared coil is to be impregnated with epoxy.

The horizontal turn orientation in Design II coil makes it well suited for the react-&-wind fabrication technique in the common coil configuration. Two Nb_3Sn coils are simultaneously wound into the coil support structure similarly to the technique developed for the single-layer common coil dipole [7]. The outer 2-3 turns have to be bent by ~15 mm or less in the "hard" direction in order to bypass the apertures. The assembly will be slightly prestressed in the vertical and horizontal directions, and impregnated with epoxy. Single coils based on this geometry and wind-&-react approach are feasible as well, although complicated ends are required.

D. Strands and Cables

The parameters of the Rutherford-type cables used in Design I and II are summarized in Table II. Both cables have a small aspect ratio and require large strands of 2-3.5 mm in diameter. It is by a factor of 2-3 larger than the diameter of the currently used Nb_3Sn strands. As a result, such cables may have rather high mechanical rigidity that may create winding problems. In case of the react-&-wind approach, the large strand diameter would require too large bending radii or cause a large critical current degradation.

TABLE II
CABLE PARAMETERS

Parameter	Design I	Design II
Strand diameter, mm	2.200	3.350
Number of strands	24	12
Cable width, mm	26.717	20.233
Cable thickness, mm	3.942	5.935
Aspect ratio	6.78	3.41

In order to avoid these problems, a multistage cable with sub-strands shown in Fig. 3 can be used. Such sub-strands allow reducing the Nb_3Sn strand diameter to the level of 0.45-0.7 mm - comfortable for the strand production, increasing the cable mechanical flexibility and minimizing the critical current degradation due to cable bending. Combination of expensive low-Cu Nb_3Sn strands and cheap pure-Cu strands allows achieving Cu:nonCu ratio in a final cable, necessary for the quench protection, at a lower cost. Samples of such cables have been fabricated and tested [8].

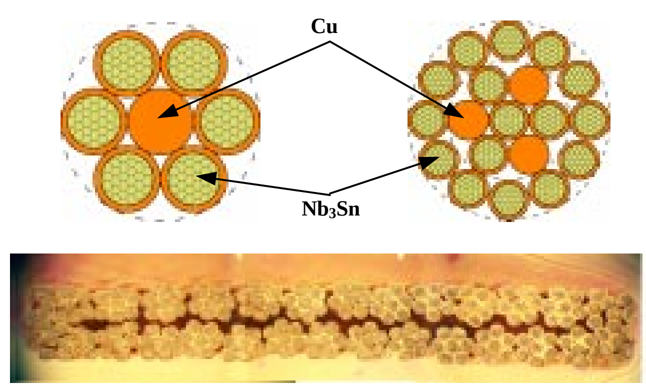

Fig. 3. Examples of strand structure combined with Cu and low-Cu Nb_3Sn strands, and cable made of such strands.

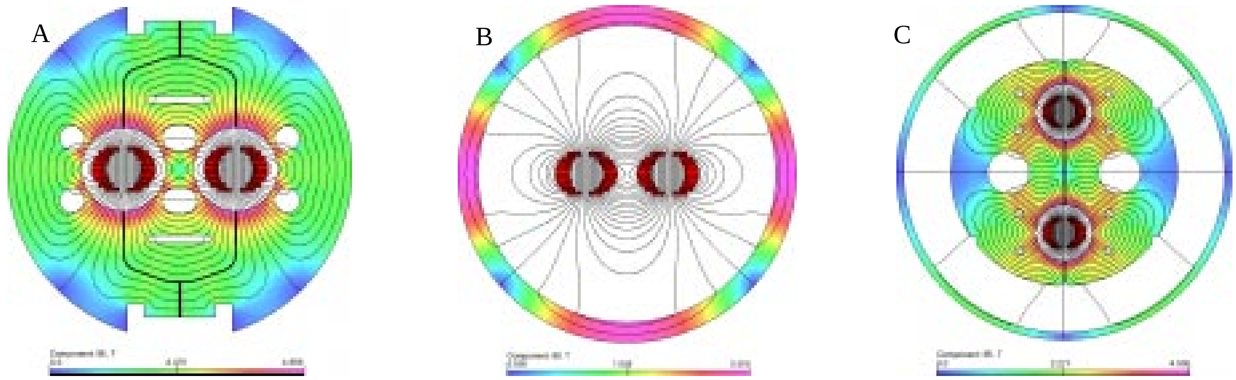

Fig. 4. 2-in-1 dipoles based on Design II coil: cold (A), warm (B) and combined cold/warm (C) iron yoke with horizontal and vertical bore arrangements.

E. Iron yoke

The optimized cross-sections of the 2-in-1 dipole magnets, based on Design II Nb_3Sn coils with cold and warm iron yokes, and with horizontal and vertical bore arrangements are shown in Fig.4. The dipole magnets with the same iron yokes can be equipped with the Design I coils as well.

In Design A, two symmetric collared coils are horizontally accomodated in a cold iron yoke. The optimal aperture separation for this configuration is 160 mm. The iron saturation effect is suppressed by optimizing the special correction holes and the yoke inner and outer diameters. The mechanical design of the similar magnet is described in [9]. The yoke is vertically split onto three pieces to allow assembly of two collared coils in the common yoke. The collared coils are prestressed by the yoke and the stainless steel skin. Since the horizontal components of the Lorentz force partially cancel each other inside the cold mass, a 10 mm thick skin is sufficient for providing an adequate coil support. The permanently open gap, designed to be parallel to the flux lines for reducing its effect on the field quality, serves for the control of coil prestress at room and helium temperatures.

In Design B, two collared coils are placed inside a cylindrical warm yoke. The minimun aperture separation that could be provided in this design is 120 mm. Magnetic coupling between the two coils generates large quadrupole and other even harmonics. They are supressed in each aperture by introducing the left-right asymmetry in the coil geometry. The yoke thickness, optimized to suppress the iron saturation effect in low-order harmonics and to reduce the fringe fields, is 35 mm. The inner radius of the yoke was chosen to be sufficient for accommodation of the cold mass, the cryostat support system and the thermal shield. The structure, based on thick aluminum rings and stainless steel inserts, proposed for the previously developed warm yoke design [9], provides the prestress and mechanical support of the collared coils. The cold mass skin is relatively thin in this design. It serves as a helium vessel and is not a part of the coil support structure.

In Design C, two symmetric collared coils are positioned vertically inside the cold yoke. The minimum aperture separation in this design when the negative magnetic coupling between the two coils is reduced to an acceptable level is 256 mm. In case of the common coil configuration with the react-&-wind approach, the bore separation may need to be increased for a comfortable bending of the reacted Nb_3Sn cable. The yoke is divided onto the cold and warm parts in order to minimize size of the magnet. The iron saturation effect is suppressed by optimizing the correction holes in the cold part, and the inner and outer radii of the cold and warm yoke parts. The cold part is vertically split onto two pieces for assembly of the two collared coils. The coil prestress is provided by the yoke and the thick stainless steel skin. The skin has to be a factor of two thicker than in Design A, since the horizontal Lorentz force from all the coil blocks is applied to the skin. The yoke gap is permanently open as in Design A for the prestress control. The distance between the cold and the warm yoke part is sufficient for accommodation of the major crygenic elements.

Designs B and C require a proper alignment of the cold mass inside of the warm yoke in order to avoid the force imbalance and distortions of the field quality. Analysis shows that the alignment requirements are modest [3] and can be easily met.

III. MAGNET PARAMETERS

The main parameters for the magnets shown in Fig. 4, are summarized in Table III. The minimum number of turns results in a low transfer function and a high nominal current, which is however less than 100 kA – the nominal current for the VLHC Stage I magnets [1].

TABLE III
MAGNET PARAMETERS

Parameter	Design A	Design B	Design C
Iron yoke ID, mm	120	440	120
Iron yoke OD, mm	490	510	480/710
Bore separation, mm	160	120	256
B/I @11T, T/kA	0.1149	0.1025	0.1100
L/aperture @11T, mH/m	0.056	0.049	0.054
W/aperture @11T, kJ/m	292.4	298.1	309.7

The quench field in the magnet aperture at 4.2 K as a function of the strand critical current density is shown in Fig. 5. For the expected in the future critical current density of 3000 A/mm^2, Cu:nonCu=1.2:1 required for magnet quench protection and critical current degradation in the coil 10% for the Design A and B (wind-&-react approach) and 15% for the

Design C (react-&-wind approach), the maximum bore fields are ~12 T as in previously developed double-layer cos-theta magnet [3]. It meets the VLHC Stage II requirements and provides ~20% critical current margin.

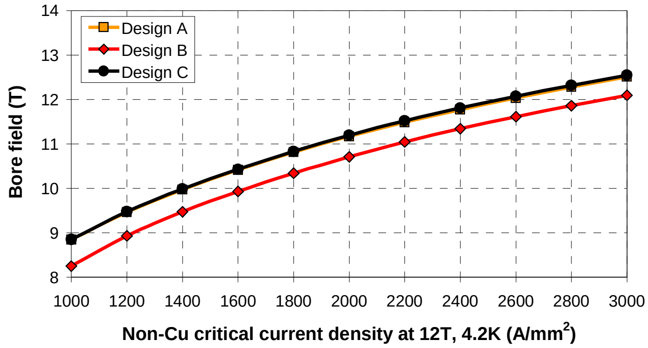

Fig. 5: Bore quench field vs. J_c in the coil at 12 T and 4.2 K.

The Table IV summarizes the systematic and random (due to ±50 μm random cable displacement) geometrical harmonics for Design I and II coils on the reference radius of 1 cm. Harmonics for asymmetric coils, required for Design B are also reported. All the coil designs provide excellent geometrical harmonics, even better than the previously developed low-current Nb_3Sn magnets [3]. A possibility of better control the random turn displacement in the precise collar structures described above, offers further reduction of the harmonics RMS spread.

TABLE IV
RELATIVE FIELD MULTIPOLES @ 1 CM IN 10^{-4}

n	Design I			Design II		
	b_n sym	b_n asym	σ_{an}/σ_{bn}	b_n sym	b_n asym	σ_{an}/σ_{bn}
1	10000	10000	1.66	10000	10000	2.05
2	-	0.0011	1.02	-	0.0005	1.07
3	-0.0001	-0.0032	0.47	-0.0016	0.0007	0.47
4	-	-0.0032	0.22	-	-0.0019	0.19
5	0.0011	-0.0018	0.10	-0.0003	-0.0031	0.08
6	-	0.0003	0.04	-	0.0011	0.03
7	0.0019	0.0060	0.02	-0.0005	0.0026	0.01
8	-	0.0106	0.01	-	-0.0033	0.00
9	-0.0035	-0.0629	0.00	0.0006	0.0013	0.00
10	-	0.0179	0.00	-	0.0025	0.00

The deviations of the low-order field harmonics due to the iron saturation effect are shown in Fig.6. They were suppressed within $\pm 10^{-4}$ up to 10 T field in all the designs.

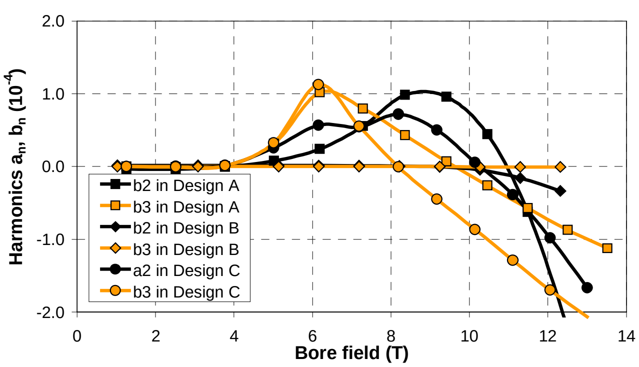

Fig. 6: Iron saturation effect on the low-order field harmonics.

IV. CONCLUSIONS

Dipole magnets based on the shell and block-type single-layer coils with minimum number of turns have been developed. All the designs achieve 11-12 T field with Nb_3Sn coils and provide the accelerator field quality. A simple single-layer coil geometry and minimum number of turns allow significant reduction of manufacturing time and cost which is essential for the magnet mass production. The collar structures, used also as coil-winding fixtures, provide precise conductor positioning and mechanical support. It offers improving the reproducibility of the field quality and the quench performance. Magnet designs are well suited for both wind-&-react and react-&-wind techniques. The low coil inductance simplifies the magnet quench protection and allows increasing the magnet length. Although a small number of turns leads to the high operating current, the recent progress in semiconductor technologies, HTS current leads and superconducting power transmission lines [1] withdraws the low current requirements for future accelerators.

Since the coils are based on the cables with small aspect ratios, the cable width can be easily increased by a factor of 1.5-2 to achieve the fields of 13-14 T. Using the SSC-type NbTi strands in these coils, allows reaching the quench bore field of ~7 T at 4.3 K and ~10 T at 1.8 K.

Optimization of the iron yoke geometry for the 2-in-1 configuration allowed reducing the bore separation distances, yoke and the magnet sizes with respect to the previously developed magnets. The magnet design with horizontal bore arrangement and warm iron yoke allows reaching the smallest bore separation of 120 mm with an acceptable field quality. This design has by a factor of ~2 smaller size and by a factor of 3.5 smaller weight than other high field magnets with the nominal field above 10 T.

V. REFERENCES

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